

TECHNICALLY speaking

BY ROB MASON, CEF, MARGO NEIDBALSON, AND MELISSA KLINGENBERG, PHD, CONCURRENT TECHNOLOGIES CORPORATION (CTC), JOHNSTOWN, PA., AND LARGO, FLA., AND PARMINDER KHABRA AND CARL HANDSY, UNITED STATES ARMY TANK-AUTOMOTIVE RESEARCH DEVELOPMENT AND ENGINEERING CENTER (TARDEC), WARREN, MICH.

Update on Alternatives for Cadmium Coatings on Military Electrical Connectors

The metal finishing industry has been impacted by numerous regulatory actions related to the hazardous materials that are used in decorative and functional coating processes. These environmental regulations are applicable to both commercial and government facilities. In addition, Executive Order (EO) 13423, *Strengthening Federal Environmental, Energy, and Transportation Management*, and EO 13514, *Federal Leadership in Environmental, Energy, and Economic Performance*, were recently enacted. These EOs require government agencies to reduce the quantity of toxic and hazardous chemicals and materials acquired, used, or disposed.

Cadmium and hexavalent chromium are very toxic and carcinogenic materials heavily regulated by the Environmental Protection Agency (EPA) and the Occupational Safety and Health Administration (OSHA). In addition, hexavalent chromium is among the three hazardous materials that the Department of Defense (DoD) has targeted for reduction to meet the requirements of the EO 13423. Due to the toxicity and carcinogenicity, as well as the numerous regulatory actions related to these materials, the U.S. Army Tank-automotive Research Development and Engineering Center (TARDEC) has been working to eliminate or reduce the use of cadmium and hexavalent chromium in ground vehicles and

related systems. The National Defense Center for Energy and Environment (NDCEE), operated by Concurrent Technologies Corporation (CTC), has been tasked to support TARDEC's activities in this area.

Specifically, the protective shells of electrical connectors currently used in military ground systems are cadmium plated and then chromated with chromate conversion coatings (CCCs) to provide additional corrosion protection. The aforementioned regulatory concerns underscore a need to find alternatives to the currently used coating processes to reduce environmental and safety risks.

However, the replacement of cadmium for any application is not a trivial task. Cadmium has been used as a protective coating for electrical connectors for many years because of the numerous

properties that it imparts to the overall component. Key properties that cadmium coatings impart to electrical connector shells include:^{1,2}

- Ease of manufacturing
- Ease of repair
- Electrical conductivity
- Electromagnetic compatibility (EMC)/electromagnetic interference (EMI) effectiveness
- Environmental resistance, particularly corrosion resistance
- Galvanic coupling

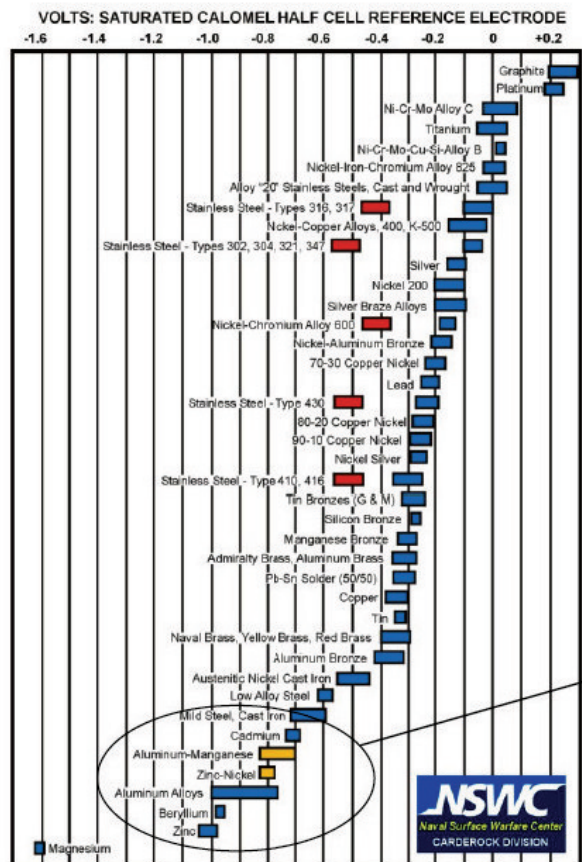


Figure 1. Galvanic series, showing position of cadmium and viable alternative metals. (Circled area: materials providing sacrificial protection.)¹

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- Inhibition of algae growth
- Low cost
- Lubricity (meets established torque/tension requirements)
- Shock resistance
- Solderability
- Temperature resistance
- Vibration resistance

CCCs are applied over cadmium coatings to provide additional properties, the most important of which are:

- Enhanced corrosion resistance
- Paintability (meets requirements for paint adhesion to coating)
- Color

As seen above, the synergistic benefits provided by this coating system have made its replacement challenging. One example of the unique protective properties that are imparted by cadmium and hexavalent chromium is corrosion resistance. Cadmium coatings provide galvanic corrosion protection to electrical connector shells, and very few metals can provide a similar level of corrosion protection in this application. This is demonstrated by the position of cadmium in the galvanic series, shown in Figure 1.¹

Figure 1 demonstrates that zinc and zinc alloys, beryllium, magnesium, and aluminum alloys are generally the most active metals in corrosive environments and, therefore, are the only materials that can provide sacrificial corrosion protection similar to cadmium in this application. However, beryllium is more hazardous than cadmium, and magnesium and pure zinc both corrode too rapidly for many engineering applications.

Other examples of the unique properties that are imparted by cadmium to connector shells involve electrical properties, specifically EMC and EMI effectiveness. Connector mating resistances must be kept to a minimum (e.g. less than 2.5 milliohms) for EMC, because greater mating resistances can lead to high voltages (and subsequent

failures) when induced by sudden surge currents (such as a lightning strike). Cadmium-plated connectors meet this requirement throughout the life of the connector (i.e., the corrosion products of cadmium are generally non-insulating). Other plated coatings, such as electroless nickel (EN), meet this requirement initially, but lose effectiveness over time due to the resistances that are generated by corrosion products.

VIAIBLE ALTERNATIVES TO CADMIUM

The DoD has been interested in cadmium replacement for many years, and numerous potential replacements have been identified and explored in past work conducted by Brooman^{2,3,4}, Gaydos⁵, Klingenberg^{3,4,6}, Legg¹, and Shahin⁷, among many others. It is the intent of this paper to summarize past work that has been accomplished in this area, with the intent of providing a rationale for the selection of the most promising candidates for further study under future phases of this current effort.

Based on the many previous studies related to cadmium replacement, and the available data on candidate technologies, a number of promising candidates for cadmium replacement were identified. Due to the particular focus of this project, candidates were limited to commercially available or near-commercial technologies. These include:

- Advanced materials
- Alloys deposited by chemical vapor deposition (CVD)
- Alloys deposited by molten salt bath processes
- Alloys deposited by ionic liquid processes
- Electrodeposited aluminum and alloys
- Electroless nickel technologies
- Electroplated tin alloys
- Electroplated zinc-cobalt
- Electroplated zinc-nickel
- Ion vapor deposited (IVD) aluminum and alloys
- Metal-filled paints and ceramics
- Sputtered aluminum and alloys

The viability of each of these processes in the context of the specific application—electrical connector shells—is discussed herein. Where data is available, issues such as compatibility of the alternatives with existing cadmium-plated connectors will be addressed.

ADVANCED MATERIALS

The use of advanced materials as a replacement for cadmium-plated parts has been considered mostly for larger aerospace components. Stainless steel is the most likely candidate to replace cadmium on larger, non-electric components. A corrosion-resistant stainless steel, S53, was developed under a project funded by the Strategic Environment Research and Development Program (SERDP). This effort^{1, 5, 8} focused on providing corrosion protection and resistance to stress corrosion cracking on aircraft landing gear. Stainless steel alloys would provide many of the necessary properties needed for electrical connector shells and may be acceptable for some applications. However, these materials generally exhibit a high mating resistance and also may not be cost-effective. Likewise, titanium alloys and Inconel® have been found to be adequate as substrate substitutes for cadmium plated fasteners⁵, but these may also be cost prohibitive for use in electrical connectors. Polymer composite materials (such as polyetheretherketone) are already in use in some commercial applications. However, military usage appears to be minimal (at least for ground vehicle applications), and consideration of this material introduces issues related to cost, conductivity, and mechanical wear for some applications. Overall, it is evident that additional research and development is required to use advanced materials to replace the standard shells in newer models of electrical connectors.

ALLOYS DEPOSITED BY CHEMICAL VAPOR DEPOSITION

The Air Force Research Laboratory (AFRL) evaluated aluminum coat-

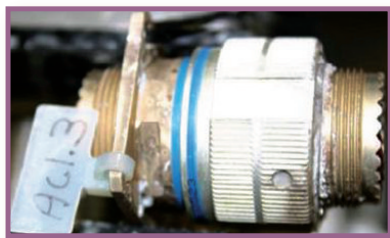


Figure 2. AlumiPlate-coated electrical connector, After 2,000 hours B117 exposure.¹²

ings applied through Atmospheric Pressure Chemical Vapor Deposition (APCVD).⁹ Environmentally benign CVD processes using triethylaluminum as a precursor for producing high-quality aluminum coatings was explored. While promising, this process involves special high-cost, equipment. Considerable further development from a process standpoint would likely be necessary to implement this process for high-volume applications such as electrical connector shells.

ALLOYS DEPOSITED BY MOLTEN SALT BATH PROCESSES

An aluminum-manganese molten salt plating process was explored under funding from the Environmental Security Technology Certification Program (ESTCP), but the process was plagued by inconsistent bath composition, visible fumes, and excessive crust formation [Ref. 10]. In addition, this process operated at a very high temperature, which is likely to affect the properties of aluminum shells. While this technology is promising, considerable further development from a process standpoint would be necessary to implement this process for electrical connector shells.

ALLOYS DEPOSITED BY IONIC LIQUID PROCESSES

As an alternative to the molten salt bath process mentioned above, the use of ionic liquids as an electrolyte to plate aluminum is under investigation.^{5,11} Ionic liquids are salts with a low melting point, which originates in their chemical structure (a mix of

anions and large organic cations). These liquid salts have unique properties that allow easy dissolution of normally insoluble chemicals, such as cellulose. Ionic liquids enable electrochemical plating of metals like aluminum; deposition rates of one micron per minute at low temperatures (60 to 100°C) have been reported.¹¹ These deposition rates are significantly superior to other low-temperature aluminum coating methods. While this process is not yet mature enough to enable the plating of commodity items such as electrical connector shells, work is progressing rapidly and promising results will be forthcoming.

ELECTRODEPOSITED ALUMINUM AND ALLOYS

AlumiPlate® is a proprietary process in which a pure aluminum coating is electrolytically deposited onto a substrate that has been immersed into a non-aqueous, fully enclosed solution in an inert atmosphere. The resulting coating is highly versatile. It can be anodized or topcoated with the standard CCC post treatment, trivalent chromium post-treatments (TCPs), or non-chrome post-treatments (NCPs). TCPs are much less hazardous than CCCs and meet requirements under the European Union's Reduction of Hazardous Substances (RoHS) Directive—although this substance is still regulated under U.S. requirements. Additionally, the AlumiPlate® process does not appear to impart hydrogen embrittlement—a concern with cadmium plating.⁵

AlumiPlate® is one of the more promising new processes for cadmium replacement on electrical connectors. Researchers at the Naval Air Systems Command (NAVAIR) conducted 2,000 hours of salt spray corrosion testing on electroplated aluminum electrical connectors with TCP^{12,13}, in accordance with ASTM B117.¹⁴ NAVAIR found that all connectors performed equal to or better than the cadmium-plated controls with respect to visual appearance of corrosion. A plated connector is shown after 2,000 hours of B117

exposure in Figure 2.¹²

From a functionality standpoint, all tested connectors met the requirement for shell-to-shell conductivity, with the exception of the AA6061 AlumiPlate® coating with TCP at 25% concentration (the most dilute). The AA6061 AlumiPlate® coating with Class III post-treatment was the top performer.

Other projects involving this process include a partnership between Lockheed, Alcoa, and the U.S. Air Force, which is evaluating several coatings, including AlumiPlate®, to replace cadmium for military and commercial fasteners.¹⁵ Based on the results from both the NAVAIR testing and this partnership, the AlumiPlate® coating is currently being qualified for electrical connectors under MIL-DTL-38999L as well as relevant internal manufacturers' specifications. Specifically, qualification and approval of the AlumiPlate® coating is anticipated for Model 38999 electrical connectors with spring fingers, which will be used on the Lockheed Martin F-35 Lightning II (also known as the Joint Strike Fighter) program.

Despite the good performance of this candidate and its recent qualification, several drawbacks remain with the use of AlumiPlate®. Due to the use of the non-aqueous electrolyte, it is unlikely that this process could meet the environmental requirements that would allow its use in a DoD facility.¹ Furthermore, the process requires the use of highly specialized equipment (e.g. high start-up cost). Finally, there are questions regarding whether the plated coating can be repaired, although initial work has found that it may be possible to use brush-plated tin-zinc to repair this coating.^{1,5}

ELECTROLESS NICKEL TECHNOLOGIES

A number of new EN-based coating systems continue to be considered for electrical connector shells. However, as mentioned previously, the corrosion properties of nickel—and subsequent electrical properties—are considerably different than

Test Descriptions	Baseline Coatings						Alternative Coatings					
	LHE Cadmium	LHE Cadmium	Titanium Cadmium	Titanium Cadmium	IVD Aluminum	IVD Aluminum	Acid Zinc Nickel	Acid Zinc Nickel	Alkaline Zinc Nickel	Alkaline Zinc Nickel	Tin Zinc	Tin Zinc
Post Treatment →	None	CCC ⁽¹⁾	None	CCC	None	CCC	None	CCC	None	CCC	None	CCC
Thickness	P	P	P	P	P	P	P	P	P	P	P	P
Bend Adhesion	P	P	P	P	P	P	P	P	P	P	P	P
Paint, Adhesion, Wet Tape	P	P	P	P	F	P	F	P	F	P	P	P
Cyclic Corrosion Unscribed	P	P	P	P	F	F	F	F	F	F	F	F
Cyclic Corrosion Scribed	F	P	F	P	F	F	F	F	F	F	F	F
Hydrogen Embrittlement	P	P	P	P	P	P	P	P	P	P	P	P
EIC, Wet	P	P	P	F	F	F	F	P	F	F	F	F
EIC, Cooked	P	P	P	F	F	F	P	P	P	P	P	P

(1) CCC Chromate Conversion Coating

■ = PASSES OR FAILS WITH INCONSISTENT RESULTS

■ = FAIL PER ACCEPTANCE CRITERIA

■ = PASS PER ACCEPTANCE CRITERIA

Table 1: Summary of Coating Performance from NDCEE Study

those of cadmium.² Further testing would be required to fully assess this candidate for military electrical connector shells. Despite these concerns, at least one leading manufacturer of electrical connectors is investigating the use of EN with occluded particles (polytetrafluoroethylene, or PTFE) as a cadmium replacement.¹⁶ While the inclusion of these particles will provide lubricity, the corrosion characteristics and electrical properties imparted to the connector shell must be considered and are being evaluated.

ELECTROPLATED TIN ALLOYS

Among the most mature and promising tin alloy coatings for electrical connector shells are tin-zinc coatings. Tin-zinc electroplating processes are mature, commercially available systems that can deposit alloys of 20–30% zinc (balance tin) from an aqueous solution. Tin-zinc coatings have been considered promising for cadmium replacement^{2,7,17}, and this finish was found to be a top performer in past studies.¹⁸ However, more recent studies have derived less positive results. An extensive study on potential cadmium replacements conducted by the NDCEE¹⁹ found that a proprietary tin-zinc coating failed both cyclic corrosion and wet notch environmentally influenced cracking (EIC) tests yet passed hydrogen embrittlement and cooked EIC. A summary of test results from this effort can be found in Table 1.¹⁹

In this study, it was noted that the deposited tin-zinc coating was found to have an insufficient amount of zinc in the deposit to provide adequate corrosion protection (less than 1% zinc, versus the anticipated >20% zinc concentration found in more corrosion-resistant coatings that had been tested under related projects). This implies that, while tin-zinc does show promise for some applications, some bath chemistries may not be robust enough to provide a consistent coat-

ing composition (and, hence, sufficient corrosion resistance) for the harsh environments to which military electrical connectors are routinely submitted. Promising results under past studies imply that this candidate could provide comparable performance to cadmium if the deposit composition could be made more consistent.

It is noted that other tin alloys, specifically tin-indium coatings, are being considered for both commercial and military applications, but these would take considerable development to be considered for electrical connector shells.

ELECTROPLATED ZINC-COBALT

Zinc-cobalt plating is typically used to finish relatively inexpensive parts that require a high level of abrasion and corrosion resistance. This coating is reported to demonstrate particularly high resistance to corrosion in sulfur dioxide environments. Several suppliers of commercial electrical connectors offer connector shells coated with zinc-cobalt as a replacement for cadmium to meet RoHS criteria. Zinc-cobalt alloys are not commonly used in applications requiring heat treatment because these alloys have been reported to demonstrate reduced corrosion resistance when exposed to high temperatures. In one study²⁰, after salt spray corrosion testing in accordance with ASTM B117¹⁴, zinc-cobalt-plated sleeves showed considerably less corrosion resistance after one hour heat treatment at 250°F as compared to the as-plated condition. While this process was initially considered as being a worthy cadmium replacement, the questionable characteristics under high-temperature environments excluded its consideration under further review.

ELECTROPLATED ZINC-NICKEL

Zinc-nickel electroplating processes are mature, commercially available systems that can deposit alloys of 5–15% nickel (balance zinc) from an aqueous solution. Zinc-nickel alloys can be deposited from both acid and alkaline processes. Boeing has found

that the alkaline process is easier to maintain and provides a more consistent coating composition.⁵ From a performance standpoint, the NDCEE found that a proprietary acid zinc-nickel coating with CCC passed bend adhesion, paint adhesion, and hydrogen embrittlement tests, but displayed only marginal EIC performance¹⁹ (see Table 1). The corrosion resistance was significantly less than the cadmium baselines, but increased coating thickness and selecting a suitable conversion coating may improve those results—although the implications of these changes to the form, fit, and function of the electrical connector would need to be identified. The proprietary alkaline zinc-nickel coating with a CCC performed similarly to the acid zinc-nickel in this study¹⁹ (see Table 1). Previous TARDEC work also found alkaline zinc-nickel coatings with a CCC to be promising for some electrical connector designs, particularly on MIL-C-83513 microminiature D-subminiature connectors, but less promising on other connector designs.

Based on these promising results, zinc-nickel has seen implementation as a cadmium replacement process in several areas. The NDCEE work¹⁹ provided information that assisted Rolls Royce Defense Aerospace in qualifying zinc-nickel as an acceptable alternative to cadmium on the T56 engine system. Boeing also found that zinc-nickel plating is an acceptable coating to replace cadmium on component parts made of low strength steel (less than 200 ksi), stainless steel, aluminum, and copper alloys.¹

Other ongoing projects involving this process include the aforementioned partnership between Lockheed-Martin, Alcoa, and the U.S. Air Force, which is evaluating several coatings, including both acid and alkaline zinc-nickel, to replace cadmium for military and commercial fasteners.¹⁵

It is recognized that both acid and alkaline zinc-nickel processes may provide an acceptable alternative coating for cadmium in many appli-

cations. Acid zinc-nickel processes have traditionally been used; however, some embrittlement issues have been related to this process.¹ For this reason, Boeing restricts the use of acid zinc-nickel to steels with ultimate tensile strength of 220 ksi or less. While these issues may not be relevant for electrical connectors, a post-process bake has been found to both relieve hydrogen embrittlement and enhance corrosion properties.² In any case, alkaline zinc-nickel appears to be the stronger candidate for this application, due to the reduction in required maintenance of the bath and the aforementioned current interest in the properties of this coating.

ION VAPOR DEPOSITED ALUMINUM AND ALLOYS

Ion vapor deposited (IVD) aluminum is a physical vapor deposition (PVD) process in which a part is placed in a vacuum chamber and glow discharge cleaned. Pure aluminum is then melted in heated ceramic boats until it evaporates and condenses on the part to form a coating. Concurrently, ions from the discharge bombard the forming coating to enhance its density.

IVD aluminum is a mature process that has been used successfully to deposit a variety of coatings for many years, and has traditionally been one of the most promising technologies for cadmium replacement. It is non-embrittling and galvanically compatible with aluminum substrates. In addition, it has excellent high temperature properties and can be conversion coated. Corrosion resistance has been reported to be comparable to, or better than, cadmium in some environments.^{2,21} Alloying the IVD aluminum coating is reported to provide even better corrosion protection; IVD aluminum-magnesium alloys with 10% magnesium have demonstrated significant pitting corrosion protection.¹⁷ Past NDCEE work found that aluminum-tungsten and aluminum-molybde-

num also demonstrated improved passivation over pure aluminum.⁶

As mentioned previously, Boeing has qualified IVD aluminum to replace cadmium on component parts made of low strength steel (less than 200 ksi), stainless steel, aluminum, and copper alloys. In a past TARDEC study, IVD aluminum demonstrated the best overall performance on aluminum connectors. Specifically, on MIL-C-38999 circular connectors, IVD aluminum performed similar to or better than cadmium, with lower shell-to-shell resistance, but slightly less corrosion resistance. It was noted that, on MIL-PRF-24308 D-sub-miniature connectors, cadmium demonstrated the best overall performance, with IVD aluminum being the best performing alternative. It was also noted that on MIL-C-83513 microminiature D-sub-miniature connectors, IVD aluminum was reported to have a significant drawback for use on these connectors. During the IVD process, aluminum coated the entire connector surface (including the phenolic material), causing the pins to be electrically continuous with each other and the connector shell, resulting in shorts and eventual connector failure.

As seen above, there are numerous drawbacks to using IVD aluminum for electrical connector shells. These include the aforementioned overcoating issues, as well as high start-up and operations costs because the equipment that is used to apply this finish is expensive. Also, while IVD aluminum is not completely limited to line-of-sight coverage, the conventional process cannot "throw" into deep recesses on some parts—particularly holes.^{1,5} There are some coating performance concerns as well. IVD aluminum coatings display a columnar structure with a high degree of porosity. As a result, the coatings must usually be glass-bead peened to densify the coating and alleviate porosity and corrosion concerns. The NDCEE found that IVD aluminum coatings, even with CCC, provide only marginal cyclic corro-

sion results¹⁹ (see Table 1), underscoring the importance of a dense aluminum coating. Also, like many pure aluminum coatings, IVD aluminum has also been reported to have poor wear resistance, and has demonstrated galling issues. The latter is a particular concern for electrical connectors; an aluminum-to-aluminum interface could result in excessive mating forces, or even unmateable connectors¹ (the incorporation of dry film lubricants have been proposed to resolve this issue, but this would have an adverse effect on electrical connectivity).

In summary, while IVD aluminum may be viable to replace cadmium in many applications, it is not anticipated to be a direct replacement for electrical connectors. In fact, an Air Force study has recognized that IVD aluminum will not easily replace more than about 50% of cadmium plating requirements.¹⁷

METAL-FILLED PAINTS AND CERAMICS

Organic paint systems that are loaded with sacrificial metals (generally aluminum and zinc metal powders) have demonstrated significant corrosion resistance in several applications. However, they are generally not considered for cadmium replacement due to poor galvanic corrosion performance and poor adhesion (compared to electroplating).⁵

Metal-filled ceramic coatings are being considered for some cadmium-replacement efforts. One supplier offers a coating that incorporates aluminum flakes in a ceramic matrix. The coating can be applied via brush or spray. It is used primarily for larger components in aircraft such as landing gear (specifically the F-22), as well as for high-temperature applications. Drawbacks to this candidate include sole source (only one supplier provides the coating, and they only license to major users), high cost, limited available data, and the requirement to heat-treat the coating before use.^{1,5} Also, coating conductivity has apparently not been determined. As such, this candidate

is likely not feasible for electrical connectors.

SPUTTERED ALUMINUM AND ALLOYS

Sputtering, or magnetron sputtering, is another PVD process. In this process, a part is placed in a vacuum chamber, where it is glow discharge cleaned after the system is evacuated. The ionized gas (typically argon) is attracted to the biased aluminum target, and aluminum atoms are ejected from the target and condense on the substrate to form a coating. The "Plug and Coat" method of sputtering allows both inner diameters (IDs) and outer diameters (ODs) to be coated within the same chamber.

Recent work conducted by Boeing¹ found that sputtering provides a better quality aluminum coating than IVD, with lower porosity. Through the "Plug and Coat" process, parts can be 100% PVD aluminum-coated (IVD Al on OD, sputter Al on ID). In addition, the process is non-hazardous as compared to cadmium plating (no air emissions, water emissions, or solid waste).

Sputtered aluminum alloys have also showed promise to replace cadmium. They include aluminum magnesium, aluminum-molybdenum, aluminum-tungsten, aluminum-manganese, aluminum-zinc, and aluminum-magnesium-zinc.^{5,6}

While promising, magnetron sputtered aluminum is still under development for coating aircraft parts. Susceptibility to environmental embrittlement has yet to be determined, and more recent work has generated mixed results.²² Also, while technically acceptable, this process involves high start-up and operational costs, and may not be cost-effective for smaller parts such as electrical connector shells.^{5,22}

OTHER DEPOSITION TECHNOLOGIES

Aluminum and its alloys can be read-

ily deposited with thermal spray processes, such as flame spray, but these coatings are usually very thick—typically 76 to 127 microns (0.003" to 0.005")—and exhibit high roughness and porosity in the as-deposited state. The process also imparts a high degree of heat to the substrate. The latter issue can be partly alleviated by utilizing "cold spray" processes; however, the former issues restrict the use of this technology for electrical connectors.

As mentioned previously, the use of ionic liquids (salt mixtures that melt below room temperature) as an electrolyte to plate aluminum is currently under investigation. This technology is a relatively new development, and while some information is available^{5,10}, the ability to adapt this process to coat electrical connector shells in mass quantities has yet to be determined.

VIABLE ALTERNATIVES TO HEX CHROME TOPCOATS

The most promising alternatives to standard CCCs at this time are TCPs. Specific applicability for electrical connectors, when used in conjunction with the AlumiPlate® process, has been promising.^{5,12,13} Further work is necessary to fully qualify TCPs as a replacement for CCCs.

NCPs are also becoming available, but these have been far less studied in this application. NAVAIR is currently continuing studies on the effectiveness of their NCPs, and AlumiPlate® offers a proprietary non-chromated topcoat over its coating system. An NDCEE Task is currently being conducted with the objective of evaluating NCPs for TARDEC.

SUMMARY

The most promising candidate coating processes to replace cadmium and hexavalent chromium in electrical connector applications are technologies that are already being used on electrical connectors to some extent, or demonstrate both considerable promise for the application and sufficient maturity. These include:

- **Electroplated aluminum (AlumiPlate®)**
- **Electroplated alkaline zinc-nickel (5-15% nickel in the deposit)**
- **Electroplated tin-zinc (at least 20% zinc in the deposit)**

Future efforts will focus on these three most promising candidates. In addition, to support efforts being undertaken by electrical connector manufacturers, two EN-based technologies, both incorporating occluded particles, will also be evaluated. Coatings with both CCCs and TCPs will be considered, as available, and cadmium with CCC will be used as the control.

The most promising candidate coating processes from emerging alternatives were also identified. These are technologies that show promise for electrical connector applications, but require further development for the electrical connectors employed by TARDEC. These include:

- **Alloys deposited from ionic liquids**
- **Magnetron sputtered aluminum alloys**
- **Tin-indium alloys**

Future efforts may consider these candidates as the technology matures and becomes more feasible for electrical connectors.

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ABOUT THE AUTHORS

Rob Mason is a Senior Technical Staff Member at Concurrent Technologies Corporation (CTC) in Largo, Fla. In this role, he provides technical support to CTC's clients in government and commercial industry. His current work includes providing support to inorganic coating activities under the NDCEE. Mason has more than 20 years cumulative experience in surface engineering, coatings R&D, and testing and evaluation methodology development, and has co-authored upwards of 40 technical publications and presentations on these subjects. He earned his B.S. in Chemistry from Fairleigh-Dickinson University, N.J. Prior to joining CTC, Mason spent six years at OMG-Fidelity, where he was heavily involved in product formulation and development, as well as technical service engineering. He is a member of the National Association for Surface Finishing (NASF), ASM International, NACE International, and Toastmasters International.

Margo Neidbalson is CTC's Program Deputy for the National Defense Center for Energy and Environment (NDCEE). In this role, she supports NDCEE Program management and operation activities. Her past technical efforts have been concentrated on evaluating hazardous plating chemistry alternatives on several NDCEE projects (non-cyanide silver plating, non-line-of-sight hard chromium alternatives, and removal of cyanide-bearing chemistries at Corpus Christi Army Depot), where she provided labora-

TECHNICALLY speaking

tory support in the evaluation and analysis of alternatives to various inorganic finishing chemistries. Neidbalson holds a B.S. in Biology from Indiana University of Pennsylvania and a M.S. in Manufacturing Systems Engineering from the University of Pittsburgh.

Dr. Melissa Klingenberg is a Principal Technical Advisor at CTC, providing overall support to the Environmental

Technologies Discipline with particular emphasis in the laser decoating and inorganic finishing areas. Her primary inorganic finishing responsibilities lie in innovative coating and surface finishing processes, with her areas of expertise being advanced vacuum deposition/surface finishing technologies and plating processes. Dr. Klingenberg received a B.S. in Chemistry and engaged in post-baccalaureate studies in Biology at the University of Pittsburgh at Johnstown. She received an M.S. in Manufacturing Systems Engineering at the University of Pittsburgh

and a Ph.D. in Materials Engineering at the Pennsylvania State University. Dr. Klingenberg has been an active member of NASF since 1994, and has presented and/or written numerous papers for NASF and AESF events and publications. In 2008, Dr. Klingenberg organized and co-chaired the first ASM International/NASF Surface Engineering for Defense and Aerospace Applications conference. In recognition of her contributions to the industry, Dr. Klingenberg recently received the Award of Merit from NASF.

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Pam Khabra holds a B.S. degree in Chemical Engineering and a M.S. in Environmental Engineering from Wayne State University. She is the Senior Engineer for the Environmental Team at the U.S. Army Tank and Automotive Research, Development and Engineering Center in Warren, Mich. Her responsibilities include providing support to Program Management Offices for elimination of hazardous materials from tactical systems, and compliance with environmental requirements. Khabra is the Technical Monitor for NDCEE Task 0470, "Cadmium and Hexavalent Chromium Free Electrical Connectors."

Carl Handsy holds a B.S. degree in Chemistry from Wayne State University and a Mechanical Engineering degree from Lawrence Technological University. He worked as research engineer on the DeLorean car at W.R. Grace and Company, and as a Development and Test Engineer at Gulf and Western Manufacturing, where he was involved in the development of electrical propulsion for automotive vehicles and load-leveling batteries for the Detroit Edison company. Handsy also worked as a Research Chemist for Occidental Petroleum in metal plating at the Udylyte Corporation prior to joining the U.S. Army Tank and Automotive Research, Development and Engineering Center in Warren, Mich., where he is a Senior Materials and Corrosion Engineer.